Phase 1 Validation Test Report at CU-Boulder: Relocation of Ground Truth events using regional P_n data based on a 1-D and a 3-D model

August, 2001 (Draft)

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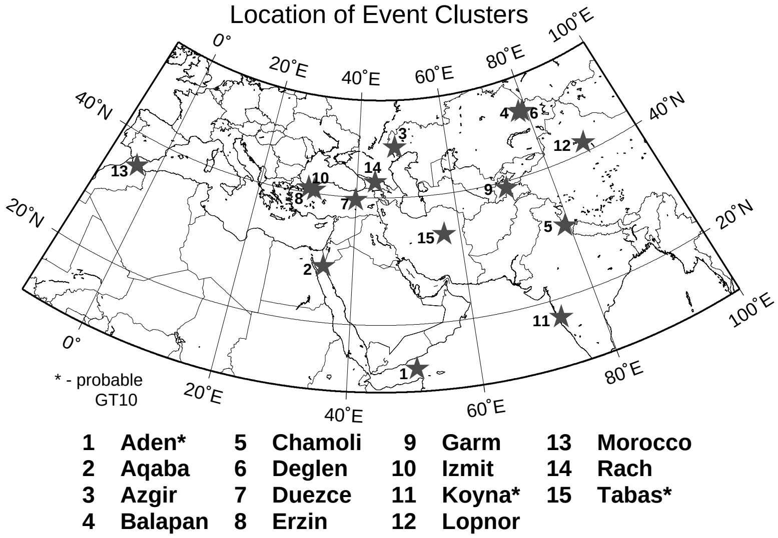

Figure 1: Location of the 15 event clusters containing the 150 events that are relocated. Most are probably GT5 in quality. The probable GT10 clusters are indicated with an asterisk.

1.0 Introduction

To complement the validation tests performed at SAIC/CMR (Yang *et al.*, 2001) as part of the Group-2 Consortium Phase 1 Validation Plan (Group-2 Consortium, 2001), we report the results of independent seismic event relocations performed at CU-Boulder. Yang *et al.* (2001) provide background information concerning the rationale and motivation for these tests.

Both studies are designed to test the ability of the 3-D model constructed at the University of Colorado at Boulder (CUB model) to locate events using regional data alone. The SAIC/CMR tests are designed to mimic more closely location methods in place at the IDC in Vienna and at the US NDC, and are applied to a larger, more diverse set of seismic events using only IMS data. The tests at CUB are based on different phase identification and location algorithms, a smaller set of mostly very well located events, and less reliable but more numerous ISC/NEIC reported travel times.

The 3-D CUB model of the crust and upper mantle is constructed on a $2° \times 2°$ grid world-wide and is described in detail by Shapiro and Ritzwoller (2001). Broadband surface wave dispersion data are used to construct this model.

The validation tests reported here are based on GT5 and GT10 seismic event locations of earthquakes and nuclear explosions that have been located using cluster analyses by Engdahl and Bergman (2001) specifically for these tests. The locations of the event clusters are shown in Figure 1 and Table 1 indicates the number of events in each cluster. Phase travel time data are taken from the EHB bulletin (Engdahl *et al.*, 1998).

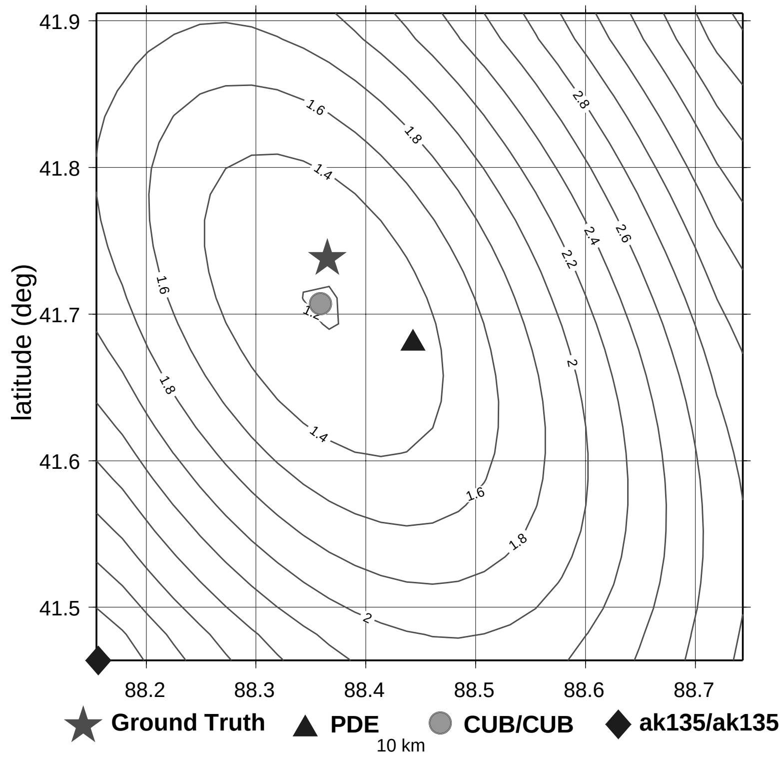

Figure 2: Misfit grid for the relocation of an event on the Lop Nor test site. Contours represent the misfit for a hypothetical event at each location on the map recorded at eight stations using the CUB model for both ray tracing and data selection and a rejection threshold of 2.5 s (CUB/CUB(2.5s)). The minimum misfit is about 1.2 s, which is identified as the location with the CUB model (shaded circle). The location in which ak135 is used for both ray tracing and data selection (ak135/ak135(2.5s)) is marked with a diamond. The Ground Truth (star) and PDE (triangle) locations are also shown for reference.

2.0 Data Set and Location Method

The purpose of this exercise is to test regional location capabilities. For this reason, we use only phase data recorded at stations within 20° of each event. Phase data are taken from a groomed version of the ISC and NEIC data bases described, in part, by Engdahl *et al.* (1998). ISC travel times are for events that occurred from 1964 through 1997 and NEIC data are from 1998 and 1999. EHB include phase measurements in their bulletin if the residual relative to the prediction from the 1-D model ak135 (Kennett et al., 1995) is less than 7.5 s for P and 15 s for S, if the event depth is within the crust or less than 50 km deep, if the azimuthal gap to all reporting stations for the event is less than 180 degrees, and if the nominal error ellipse is less than 1000 km^2 in area. We refer to this data set as the EHB bulletin. In these tests, we employ only data identified as P_n by EHB. The phase picks themselves are simply ISC or NEIC reported data, but the phase identification and data rejection are peformed by EHB.

Event locations are obtained by grid-search, in which rms misfit to observed travel times

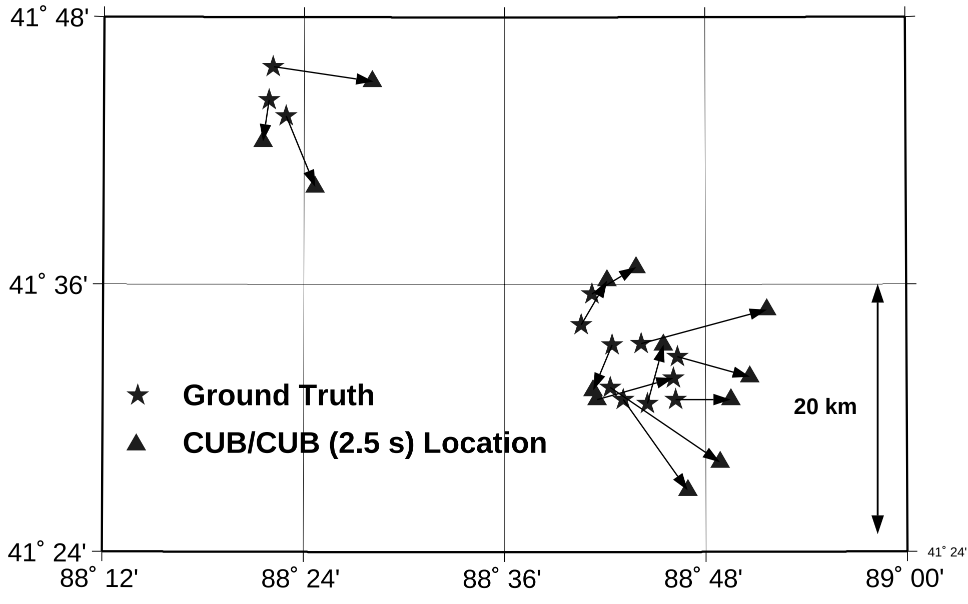

Figure 3: Mislocation vectors for the 13 events composing the Lop Nor event cluster. The GT locations are shown with a star and the locations using the CUB model for both ray tracing and data selection with a rejection threshold is 2.5 s (CUB/CUB(2.5 s)) are shown with the triangles.

is the functional we seek to minimize. Epicentral location and origin time are the three unknowns. Event depth is fixed to the value determined in the cluster analysis. This is done because event depth trades-off strongly with origin time and, to first-order, is independent of the epicentral location for shallow crustal events. Fixing event depth, therefore, has little effect on the error in the epicentral location,

Because erroneous travel time data remain in the EHB bulletin, particularly for regional phases, further outlier rejection is needed prior to location. EHB reject P travel times more than 7.5 s different from the travel time predicted from the 1-D model ak135 using their relocation. We report results below using several different rejection schemes. Each scheme is based on the travel time predicted from the PDE location for a particular model and a specified misfit rejection threshold. For example, we refer to the rejection of travel time observations more than 2.5 s from the prediction of the CUB model as the CUB(2.5 s) rejection scheme. It is possible to use a different model for data rejection than for location. Thus, if ak135 is used to locate events with data rejected using the CUB model and the 2.5 s rejection threshold, we refer to the scheme as ak135/CUB(2.5 s). We report here locations for the following schemes: CUB/CUB, ak135/CUB, ak135/ak135 in which the threshold is set at 2.5 s, 3.5 s, and 5.0 s.

An example of the rms misfit grid for an event at Lop Nor is shown in Figure 2 and Figure 3 shows the mislocation vectors for the 13 events that compose the Lop Nor cluster.

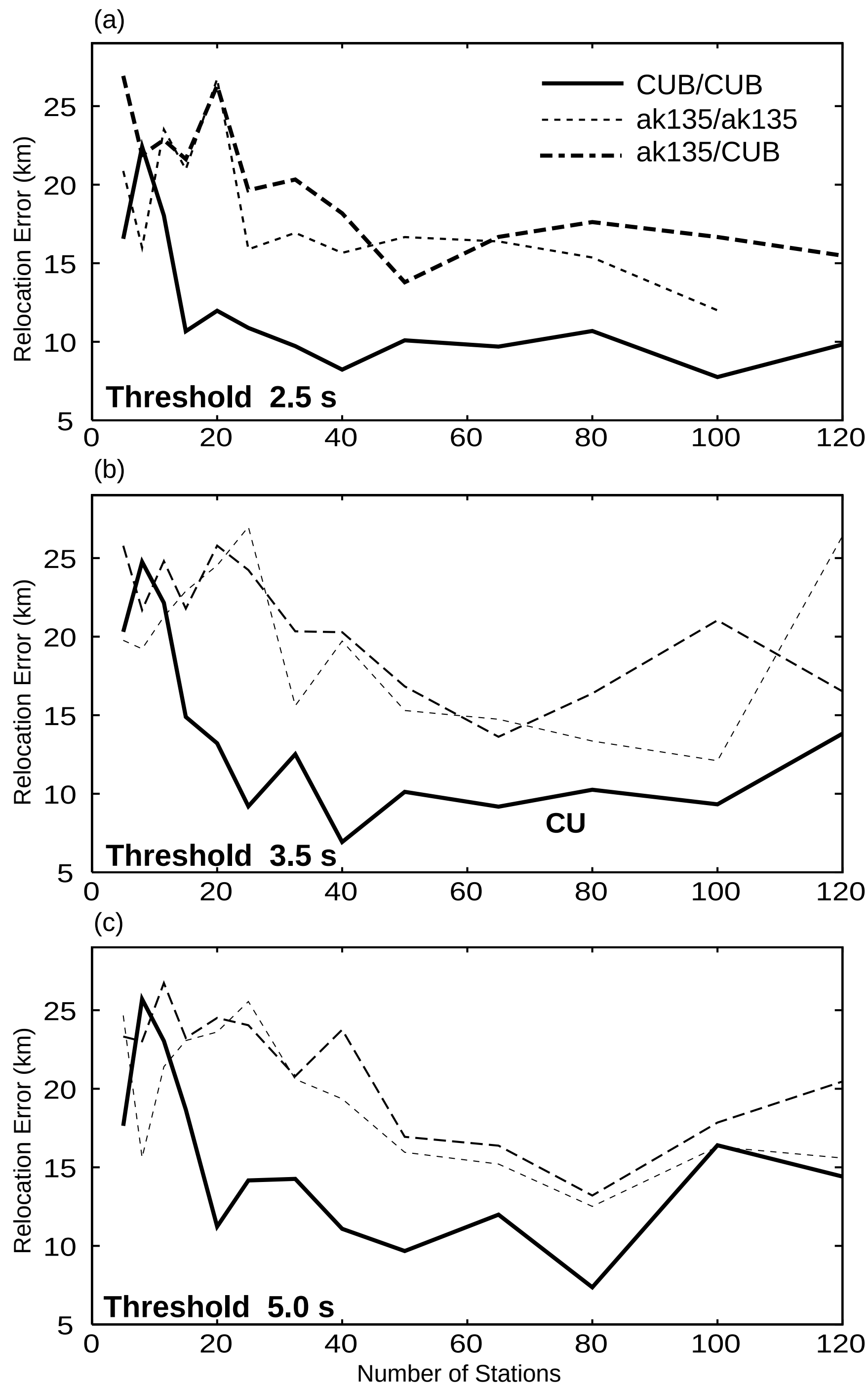

Figure 4: Location error as a function of number of stations used in the location, segregated from top to bottom by the rejection threshold. Locations using the CUB model both for tracing and data selection (CUB/CUB) are shown as solid lines, using the ak135 model both for ray tracing and data selection (ak135/ak135) are shown as dotted lines, and using the ak135 for ray tracing but the CUB model for data selection (ak135/CUB) are shown as the long dashed lines. Data rejection thresholds are 2.5 s, 3.5 s, and 5.0 s in (a) - (c), respectively.

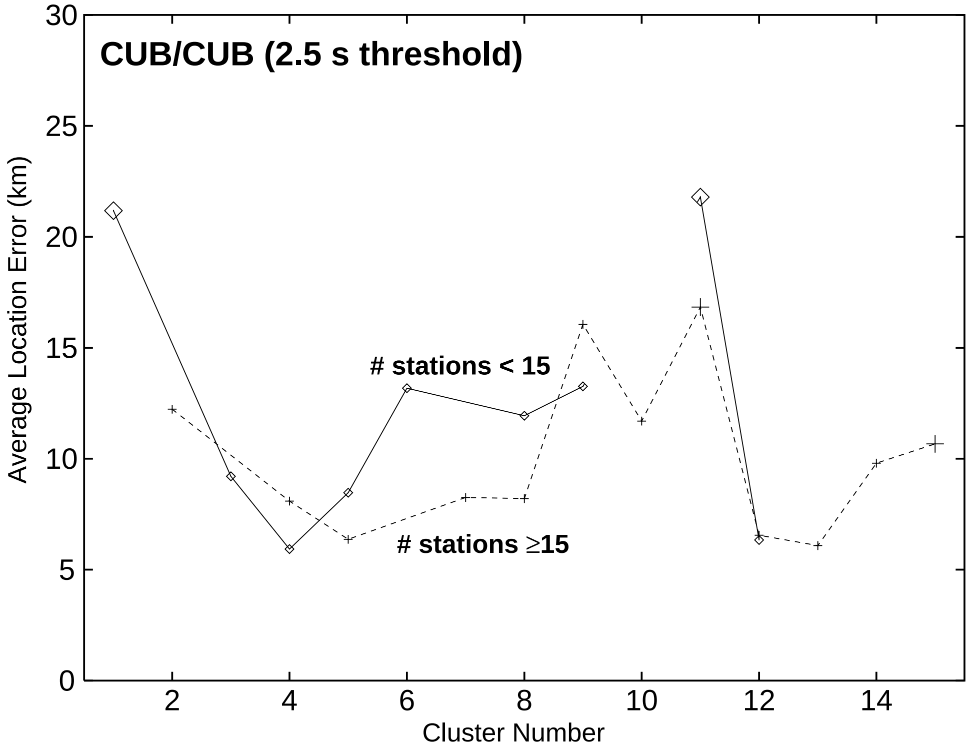

Figure 5: Average location error for each of the 15 clusters identified in Figure 1. The solid and dotted lines indicate the error for those events recorded at more than or less than 15 stations, respectively. The larger symbols indicate the GT10 clusters (clusters 1, 11, and 15), for which the "location error" is expected to be inflated due to the uncertainty in the GT location.

3.0 Results

The quality of the location is equated with the difference between the estimated location and the GT location for each of the 150 events. This difference is called the "location error". In the case of the GT10 events, in particular, a substantial fraction of this "error" may result from the error in the GT location. Results are summarized in Figures 4 - 6 and Tables 1 - 3.

An overall summary for each of the 15 event clusters is presented in Table 1. The average number of stations listed there is for the CUB (2.5 s) selection criterion. Location error and rms misfit at the estimated epicenter are presented. Typical location errors for the CUB/CUB(2.5 s) location scheme are 10 - 15 km, with larger errors for the GT10 events. Rms-misfit averages about 1.06 s for the CUB (2.5 s) rejection threshold using the CUB model, but grows to 1.33 s and 1.56 s for the CUB (3.5 s) and CUB (5.0 s) thresholds, respectively, and, on average, grows with epicentral distance.

The key predictive variable that explains location error is the number of reported phases (or stations) used in the location. Figure 4 shows how location error changes with the number of reporting regional stations. For the CUB/CUB locations, a simple error model is apparent. On average, location error decreases as the number of station increases with

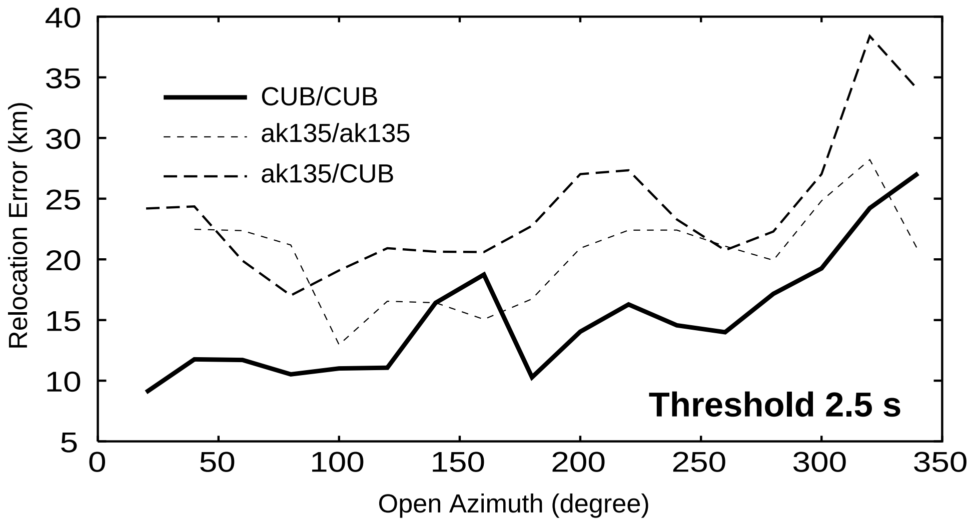

Figure 6: Location error as a function of open azimuth defined by the stations used in the locations. Locations using the CUB model both for tracing and data selection (CUB/CUB) are shown as solid lines, using the ak135 model both for ray tracing and data selection (ak135/ak135) are shown as dotted lines, and using ak135 for ray tracing but the CUB model for data selection (ak135/CUB) are shown as the long dashed lines. The data rejection threshold is 2.5 s in all three cases.

a knee between about ∼15 - 25 stations depending on the rejection threshold, and then flattens out to reach a large station-number asymptote of 10-13 km (which also depends on the rejection threshold). The pattern for the ak135/ak135 locations is similar, but changes less with the data rejection threshold. In general, for ak135/ak135, the knee in the curve appears at 25-40 stations and location error asymptotically approaches about 18 km.

Table 2 presents summary results for all events and location schemes depending on whether the number of reporting stations is less than or greater than 15. On average, the CUB/CUB location error is about 11 km and the ak135/ak135 location is about 20 km. The difference in the accuracy of the locations between these two schemes reduces appreciably if the number of reporting stations is less than 10. Table 3 summarizes the percentage of events for which the CUB/CUB scheme yields better locations than the ak135/ak135 scheme. If the number of reporting stations is greater than 15, the CUB/CUB locations are better than the ak135/1k135 locations for about 3/4 of the events. If there are fewer than 15 reporting stations, CUB/CUB locations are more accurate for about 2/3 of the events.

Another predictive variable is open azimuth, which is correlated with the number of reporting stations. Figure 6 shows location error as a function of open azimuth for the three location schemes CUB/CUB, ak135/ak135, ak135/CUB and a rejection threshold of 2.5 s. For CUB/CUB, if open azimuth is less than about 180°, location error is nearly flat and equal to about 10 km. Above 180°, location error grows as it does with decreasing station number. Similar trends are apparent for the other two location schemes.

In summary, the largest positive effects of using a 3-D model become apparent with relatively good station coverage. If the number of reporting stations is greater than about 15, the CUB model is expected to deliver locations that are nearly twice as accurate as ak135, on average, and are better than the ak135 locations for about 3/4 of the events. If the number of stations is less than about 10, however, this difference becomes blurred.

4.0 Summary and Conclusions

The relocation of 150 events from 15 event clusters using regional P_n data has yielded the following principal conclusions:

- The quality of locations depends strongly on the data rejection criterion. This is due in part to erroneous travel time measurements and phase misidentifications in the EHB bulletin.

- The 3-D CUB model delivers significantly improved regional locations over the 1-D model ak135 on average. The key predictor of location accuracy is the number of reported P_n phases used in the location. If the number of reported phases is greater than 15, CUB improves the location for about 3/4 of the events and location error relative to ground-truth averages about 11 km compared with 19 km for ak135. If the number of reported phases is less than 15, the differences between the locations using the 3-D and the 1-D models begins to blur.

There are two principal directions for future improvements in this validation test. First, it is important to sharpen our understanding of the location accuracy with a relatively few reported phases. We have reported results here that show that the difference in location accuracy between a 1-D and a 3-D model reduces as the number of reporting stations decreases below about 15. More careful tests are needed to fine-tune this result and to address, in particular, the likely location errors for small events observed only at a few stations as part of nuclear monitoring. Second, it is also desirable to understand how including other phases, both regional and teleseismic, will affect location accuracy. It would be useful to know the effect of using a few S_n and P_g phases or a few teleseismic arrivals, particularly if the number of regional P_n phases is small.

5.0 Tables

Table 1. Summary Results of Relocation Tests Using the CUB and the Models (Data selection threshold is 2.5 s.)

				CUB/CUB(2.5 s)		ak135/CUB(2.5 s)		ak135/ak135(2.5 s)	
n	Cluster	# events	aver. # stat	Error (km)	rms (s)	Error (km)	rms (s)	Error (km)	rms (s)
1	Aden*	6	6	21.2	0.89	26.1	0.99	26.4	1.01
2	Aqaba	12	44	12.2	1.16	16.7	1.27	15.9	1.20
3	Azgir	6	8	9.2	1.06	31.2	1.81	27.8	1.46
4	Balapan	11	20	7.7	1.03	25.8	1.60	26.8	1.32
5	Chamoli	10	15	7.4	0.88	23.9	1.39	13.7	0.39
6	Deglen	12	8	9.8	0.90	24.5	1.00	25.3	0.80
7	Duezce	16	43	8.3	1.08	14.5	1.53	13.6	1.21
8	Erzin	6	54	8.8	1.29	27.8	2.03	25.9	1.86
9	Garm	16	13	14.1	0.89	17.3	1.63	13.9	0.96
10	Izmit	8	78	11.7	1.08	12.8	1.31	5.8	1.05
11	Koyna*	8	10	21.2	0.76	23.6	0.90	25.6	0.89
12	Lop Nor	13	20	6.5	1.04	24.0	1.74	23.5	1.49
13	Morocco	2	68	6.1	1.32	24.5	1.37	24.4	1.15
14	Racha	11	57	9.8	1.37	17.7	1.23	22.1	1.19
15	Tabas*	12	26	10.7	1.11	23.5	1.56	18.7	1.37

* - GT10

Table 2. Average Relocation Errors for Different Models and Data Rejection Criteria

CUB/CUB			
Threshold	# stat $<$ 15	# stat $\geq$ 15	all stat.
2.5 s	12.7 km	9.7 km	10.8 km
3.5 s	14.9 km	10.6 km	11.9 km
5.0 s	14.4 km	11.8 km	12.5 km
ak135/CUB			
Threshold	# stat $<$ 15	# stat $\geq$ 15	all stat.
2.5 s	24.1 km	19.7 km	21.3 km
3.5 s	24.4 km	20.2 km	21.4 km
5.0 s	24.8 km	20.7 km	21.8 km
ak135/ak135			
Threshold	# stat $<$ 15	# stat $\geq$ 15	all stat.
2.5 s	21.4 km	17.9 km	19.7 km
3.5 s	21.7 km	18.6 km	19.8 km
5.0 s	21.1 km	19.4 km	20.0 km

Table 3. Comparison of Relocation Results for Different Models

CUB/CUB better than ak135/ak135			
Threshold	# stat < 15	# stat ≥ 15	all stat.
2.5 s	71.2%	76.5%	74.7%
3.5 s	65.0%	74.5%	72.0%
5.0 s	73.5%	75.9%	75.3%

6.0 References

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